THE INTEGRITY OF WATER

Proceedings of a Symposium

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U.S. Environmental Protection Agency
Office of Water and
Hazardous Materials

THE INTEGRITY OF WATER

a symposium

SYMPOSIUM COORDINATORS:
R. Kent Ballentine and Leonard J. Guarraia
Water Quality Criteria Staff, EPA
Washington, D.C.

OPENING SESSION

Chairman: Kenneth M. Mackenthun, Acting Director, Technical Standards Division, Office of Water and Hazardous Materials, EPA, Washington, D.C.

Speakers: Kenneth M. Mackenthun

James L. Agee, Assistant Administrator, Office of Water and Hazardous Materials, EPA, Washington, D.C.

Thomas Jorling, Director, Center for Environmental Studies, Williamstown, Massachusetts

Donald Squires, Director, State University of New York Sea Grant Program, Albany, New York

CHEMICAL INTEGRITY

Chairman: Dwight G. Ballinger, National Environmental Research Center, EPA, Cincinnati, Ohio

Speakers: Bostwick Ketchum, Director, Woods Hole Oceanographic Institute, Woods Hole, Massachusetts

Arnold Greenberg, Chief, Chemical and Radiological Laboratories, State of California Department of Public Health, Berkeley, California

Jay Lehr, Executive Secretary, National Water Well Association, Columbus, Ohio

PHYSICAL INTEGRITY

Chairman: Richard K. Ballentine, Water Quality Criteria Staff, EPA, Washington, D.C.

Speakers: Donald J. O'Connor, Professor of Environmental Engineering, Manhattan College, New York, New York

Donald R. F. Harleman, Professor of Civil Engineering and Director, Parson's Laboratory for Water Resources, Massachusetts Institute of Technology, Cambridge, Massachusetts

John M. Wilkinson, A. D. Little, Inc., Cambridge, Massachusetts

BIOLOGICAL INTEGRITY— A QUALITATIVE APPRAISAL

Chairman: Leonard J. Guarraia, Water Quality Criteria Staff, EPA, Washington, D.C.

Speakers: David G. Frey, Indiana University, Bloomington, Indiana

George Woodwell, Brookhaven National Laboratories, Upton, Long Island, New York

Charles Coutant, Oak Ridge National Laboratory, Oak Ridge, Tennessee

Ruth Patrick, Chief, Curator of Limnology, Academy of Natural Sciences, Philadelphia, Pennsylvania

BIOLOGICAL INTEGRITY— A QUANTITATIVE DETERMINATION

Chairman: David G. Frey, Indiana University, Bloomington, Indiana

Speakers: Ray Johnson, National Science Foundation, Washington, D.C.

John Cairns, Virginia Polytechnic Institute and State University, Blacksburg, Virginia

Gerald T. Orlob, Resource Management Associates, Lafayette, California

J. P. H. Batteke, Chief, Social Sciences Division, Environment Canada, Burlington, Ontario

INTEGRITY—AN INTERPRETATION

Chairman: Martha Sager, Effluent Standards and Water Quality Information Advisory Committee, EPA, Washington, D.C.

Ronald B. Robie, Director, Department of Water Resources, The Resources Agency, Sacramento, California

Ronald B. Outen, National Resources Defense Council, Washington, D.C.

R. M. Billings, Director of Environmental Control, Kimberly-Clark, Neenah, Wisconsin

Gladwin Hill, National Environmental Correspondent, New York Times, New York

Following each presentation, Symposium participants were encouraged to question the speaker. These discussions were recorded by a professional reporting service and appear at the conclusion of each paper. They have been minimally edited, simply for clarification of the spoken word in print.

FOREWORD

"The Integrity of Water" results from the formal papers and comments presented at an invitational symposium by recognized water experts representing a variety of disciplines and societal interests. The focus of the symposium was on the definition and interpretation of water quality integrity as viewed and discussed by representatives of State governments, industry, academia, conservation and environmental groups, and others of the general public. The symposium was structured to address quantitative and qualitative characteristics of the physical, chemical, and biological properties of surface and ground waters.

It is recognized that streams, lakes, estuaries, and coastal marine waters vary in size and configuration, geologic features, and flow characteristics, and are influenced by climate and meteorological events, and the type and extent of human impact. The natural integrity of such waters may be determined partially by consulting historical records of water quality and species composition where available, by conducting ecological investigations of the area or of a comparable ecosystem, and through modeling studies that provide an estimation of the natural ecosystem based upon information available. Appropriate water quality criteria present quality goals that will provide for the protection of aquatic and associated wildlife, man and other users of water, and consumers of the aquatic life.

This volume adds another dimension to our recorded knowledge on water quality. It brings into sharp focus one of the basic issues associated with the protection and management of this Nation's valued aquatic resource. It highlights, once again, our unqualified dependence upon controlling water pollution if we are to continue to have a viable and complex society. The Congress has provided us with strong and comprehensive water pollution control laws. In accordance with the advances in research and development and with our increased knowledge about the environment, these laws will receive further congressional consideration and modification as appropriate. It is through the efforts of those who participated in making this volume possible that attention is focused once again on the basic goals of water quality to support the dynamic needs of this generation and of others to come.

Douglas M. Costle, Administrator
U.S. Environmental Protection Agency
June, 1977

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BIOLOGICAL INTEGRITY OF WATER—AN HISTORICAL APPROACH

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To a considerable extent the topics assigned to us have unreasonably artificial boundaries, because an ecologist cannot talk about the physics, chemistry, or biology of water separately, nor about the qualitative aspects of water and its biotas separately from the quantitative aspects. Moreover, in a meeting such as this of persons with disparate backgrounds and interests, effective communication can be a problem. We all tend to use words that have special meanings within our own disciplines and we assume a certain understanding of premises, principles, and laws when we use them. To make certain that we all are operating on the same wave length I shall present several principles of ecology that must guide our thinking about water, its management, and the potential effects on it of various manipulative processes, then give my own definition of the integrity of water, and finally address the topic assigned me. The principles to be discussed apply to all aquatic systems, but the examples I shall present will be concerned chiefly with lakes, as they, along with the oceans, provide in their sediments the only record of past events not covered by written observations or the memory of persons still living.

(1) Lakes and rivers are integral parts of larger systems—the watersheds or catchment areas that are drained by the rivers or drain through the lakes. Besides water itself, the catchment area contributes dissolved and particulate substances, both mineral and organic. In addition, usually lesser quantities of various substances are contributed directly to the water from the atmosphere by precipitation and dry fallout. Together with such process-regulating variables as light, temperature, current velocity, et cetera, these various substances comprise the abiotic portion of the aquatic environment and help control the diversity and abundance of aquatic organisms.

(2) Those substances that are used directly by aquatic organisms and are necessary in their metabolism—usually called essential nutrients—are recycled in the system by biological mechanisms. Storage in living biomass, in wood or sediments, or in the deep water of a stratified lake can delay the reutilization of these nutrients for varying periods of time. Because inputs and outputs, including storage, are generally in balance, an aquatic system to remain functional requires a continuous input of nutrients. The quantities of nutrients and other substances contributed by a watershed vary with the geological nature of the substrate and its overlying soils, the vegetational cover of the land, and climate. Since all of these tend to form regional patterns, it is not surprising that rivers and lakes also tend to form regional patterns or clusters in their chemistry, productivity, and biotic diversity.

(3) Besides nutrients there must also be a source of fixed energy, mostly in organic compounds. The latter derive both from photosynthesis accomplished within the aquatic part of the system and from organic materials, such as leaves, pollen, and leachates produced in the terrestrial part of the system. In some systems, such as lakes with small, nonforested watersheds, virtually 100 percent of the available energy derives from autochthonous photosynthesis, whereas in other systems, such as small, headwater streams in heavily forested regions, almost all the fixed energy derives from organic detritus of terrestrial origin. But whatever its origin, the fixed energy in organic substances is the driving force that enables the organisms present to metabolize and carry on their life processes. As the energy is used in metabolism it is transformed into heat and dissipated from the system. Hence, unlike nutrients, energy cannot be recycled. It is a one-way street, but like nutrients there must be a continuous supply for the ecosystem to function.

(4) Taking into consideration regional differences in water chemistry and nutrient supply and differences between water bodies in energy availability and efficiency of nutrient recycling, each aquatic system has accumulated over time a diversified biota consisting of many species of organisms ad-

justed to the particular set of conditions in the water body in question. For purposes of analysis and construction of models, these organisms are often clustered into such functional groups as primary producers, herbivores, detritivores, carnivores, decomposers, et cetera, but all are interrelated. That particular species occur in a given lake or river is partly a matter of the species pool of the region and the dispersal capabilities of the individual species, partly a function of the biotic and abiotic relationships in the water body. Although we consider these systems to be in a steady state, intuitively we expect the biota to adjust to long term changes in climate, vegetation, soil development, and internal trends within the system itself, and we also expect the system to be able to accommodate and eventually recover from such short term natural stresses as scouring flushouts in rivers, episodes of volcanism, landslides, and so forth. Homeostasis is restored.

This, to me, is what is meant by the integrity of water—the capability of supporting and maintaining a balanced, integrated, adaptive community of organisms having a composition and diversity comparable to that of the natural habitats of the region. Such a community can accommodate the repetitive stresses of the changing seasons. It can accept normal variations in input of nutrients and other materials without disruptive consequences. It displays a resistance to change and at the same time a capacity to recover from even quite major disruptions.

My assignment is to consider what history tells us about the response of aquatic systems. Anything that happened in the past is history. Even the words I speak become a part of history as soon as they are spoken. But most of history is unrecorded and hence unavailable for interpretation. In the case of aquatic systems there are anecdotal accounts of particular events or conditions that may have some comparative value. There may be time series of accumulated data for particular rivers or lakes that document what happened during these intervals. And, in the case of lakes (and oceans), the accumulated sediments constitute an historical record of changing climate and watershed conditions and the integrated response of the lake to these changes. Where no previous studies on particular lakes exist and likewise no isolated anecdotes about particular events, the only means we have of interpreting previous conditions is from the sediments. For rivers this possibility does not exist at all, as there is no long term sequential accumulation of sediments. Hence, here we are completely dependent on the written record, except for the geomorphic and hydrologic changes that can be interpreted from the landscape and residual sediments of the valley.

I do not intend to say much about rivers. Their response to point source additions of domestic and industrial wastes is the establishment of a longitudinal gradient involving a succession of chemical processes and organisms, which for organic wastes is sufficiently predictive that a series of zones—the sabrobic system—has been set up to help describe and interpret the process of recovery. Other zone designations have been devised for various kinds of industrial wastes and the responses they elicit.

Organisms vary greatly in their sensitivity to environmental changes accompanying pollution. Fishes together with a majority of insects and molluscs are most sensitive. Blue-green algae and a few miscellaneous animals from several groups are most resistant. These differences in tolerance lead to a greatly simplified community at the point of maximum impact, with the organisms tolerating the conditions here often occurring in tremendous numbers, and then to a gradual buildup in diversity of species and equitability in numbers of individuals downstream. Various diversity indices have been proposed to help quantify these changes. Diatoms are particularly useful in stream studies and their truncated log-normal distributions are useful in assessing the severity of pollution. The experienced investigator can often determine quite easily from the macroinvertebrates present what the stage of recovery is, and can also detect residual effects of pollution, as from lead mines in Wales, that are no longer detectable chemically.

Lakes are fundamentally different from rivers in a number of respects that affect the integrity of water as I have defined it. In the first place, their water movements are not gravity-controlled, unidirectional flows which continually flush out the channel with new water from above, but rather wind-induced circulations. Typically in summer, when the wind is not adequate to overcome the differences in density set up by surface warming, the lake becomes divided into an upper circulating epilimnion and a lower zone, the hypolimnion, cut off from the surface by a steep density gradient and as a result subject to generally much weaker water movements than the epilimnion. During periods of calm weather those lakes that circulate continuously over summer can become temporarily stratified and even the epilimnion of the others can develop secondary stratifications under these circumstances. Regardless of the duration of such stratification, the hypolimnion, or its equivalent in temporary stratification, experiences cumulative chemical changes, most important of which is the gradual depletion of dissolved oxygen by biological activity. The longer the duration of stratification and the greater the amount of biological activity, the more severe will be the oxygen depletion with its attendant stresses on organisms requiring certain levels of dissolved oxygen for their survival.

Unlike rivers, lakes accumulate sediments progressively and sequentially. One effect of these sediments is gradually to reduce the volume of the hypolimnion over time and hence the total volume of dissolved oxygen it contains when stratification becomes established in spring or summer. Consequently, even without any increase in biological activity, the hypolimnion will experience a gradual reduction in oxygen concentration over time, which brings about the extinction and replacement of various deepwater organisms as their tolerances for low oxygen are exceeded.

The sediments constitute a storage for energy and nutrients. Some of this is utilized by bacteria which can continue their activity even to considerable depths in the sediments, or by various animals, which because of their need for molecular oxygen are confined generally to the uppermost few centimeters. Whether the sediments are functioning chiefly as a sink or as a reservoir for nutrients is important in problems concerning eutrophication and its management.

The sediments also constitute a chronological record of processes in the lake and conditions in its watershed, including climate. A perceptive reading of the record—its chemistry, physics, and paleontology—gives us much insight into the stability of lake systems when subjected to various stresses, including those resulting from man's activities, and their rates of recovery.

A third major difference between rivers and lakes is that the water in lakes has a certain residence time, up to 100 years or more in some of the large lakes, determined by the relationship between the input of water from the catchment area and direct precipitation and the total volume of the lake. This allows for the recycling of nutrients in the same place, subject to the constraints imposed by stratification, and the buildup of a diverse community of small floating organisms—the plankton. And even apart from any storage function of the sediments, the residence or replacement time means that there is an inherent lag in response of the system to any increase or decrease in inputs of nutrients or other substances having biological effects. In streams the response to input changes can be almost immediate. Any storages in the sediments are mostly temporary, as the sediments can be swept downstream during the next flood stage.

What I should like to do now is present a few examples of the kinds of responses made by lakes to various stresses.

It was almost axiomatic in limnology until quite recently that lakes increase in productivity over time through natural causes, a process that has been termed natural eutrophication. This idea seemed to be substantiated by some early studies in paleolimnology which showed that the organic content of the sediments increased exponentially over time from a very low level initially to a certain plateau level—the trophic equilibrium—which was then maintained essentially unchanged almost to the present. The trophic equilibrium was regarded as a state in which production was no longer limited by nutrient supply but rather by such factors as light penetration that affect the efficiency of utilization and recycling of nutrients within the system.

The sedimentary chlorophyll degradation products (SCDP) in sediments originate almost entirely from photosynthetic plants, chiefly algae, in the lake itself. Present evidence suggests that these organic compounds are relatively stable in sediments. Hence, the quantitative changes over time of these substances can give an indication of the magnitude and changes in productivity experienced by a lake. One core from Pretty Lake, Ind., (Figure 1), shows low SCDP and hence low productivity in late glacial time and then an exponential increase to a maximum, maintained essentially at plateau level almost to the present. This corresponds to the classical interpretation of the trophic equilibrium in lake ontogeny. But the second core from shallower water shows a decline in SCDP after the maximum following the exponential increase, which does not fit the model.

We now know from this and other studies in paleolimnology that change in productivity over time is not unidirectional from low to high in all lakes, but that some lakes had a period of high productivity initially and then became less productive subsequently. Others had discrete episodes of higher productivity from whatever cause. For example, Lake Trummen in southern Sweden (Digerfeldt, 1972) had high accumulation rates of organic matter, nitrogen, and phosphorus at the beginning of postglacial time approximately 10,000 years ago. These subsequently declined and remained low up to very recent time, when industrial organic effluents completely changed the character of the lake (Figure 2). These relationships are interpreted as reflecting the high early availability of nutrients from the youthful soils of the regional till sheets, with the subsequent decline resulting from the progressive impoverishment of the soil by leaching and by the reduction of subsurface inflow into the lake as basin-sealing sediments accumulated.

Hence, the productive status of a lake is depend-

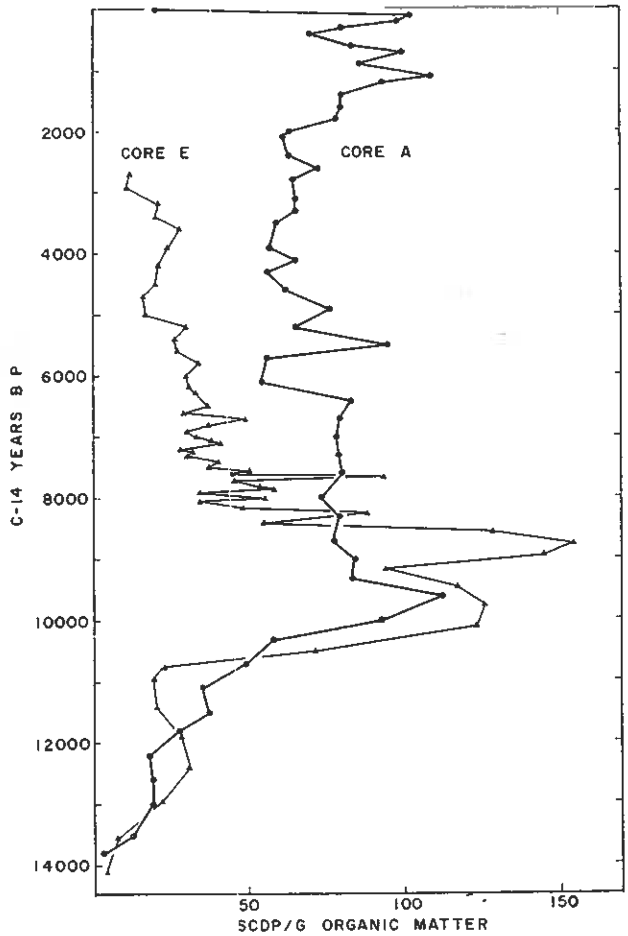


FIGURE 1

ent on the magnitude of its nutrient inputs, subject to the internal controls of the system. If we can decrease the nutrient supply, we can expect a more or less commensurate decrease in productivity. Various attempts are being made to model the magnitude of the response expected from any reduction in nutrient loading, but the rate of response is still unpredictable. The rapid reduction of phosphorus and productivity in Lake Washington following the elimination of secondary sewage effluents (Edmondson, 1972) is encouraging, although some other components of the system, such as nitrogen, did not behave in the same dramatic way. Other examples to be presented suggest that the response time of the total system, or perhaps better the rebound time from a stressed condition, can be much longer than in Lake Washington.

The responses of a lake to the decreasing oxygen concentration of the hypolimnion over time are instructive and significant. Western Lake Erie is so shallow that it stratifies only temporarily in summer during calm weather. Already by 1953 the oxygen demand of the sediments had become such that during a brief period of temporary stratification in late summer the oxygen content of the water overlying the bottom was sufficiently reduced to cause the wholesale death of the nymphs of the burrowing mayfly, one of the most abundant organisms here and a very important fish food (Britt, 1955). The mayflies never reestablished their populations but they have been replaced by smaller oligochaete worms capable of enduring quite low concentrations of dissolved oxygen. Thus, a single event, although obviously with antecedent conditions, led to a complete change in one portion of the biotic community.

The cisco is another case in point, although perhaps less spectacular. If we want to talk about endangered species, or at least endangered populations, this is one. It is a fish that lives in deep water with requirements for both low temperature and high oxygen. If either of these limits is exceeded, the fish perishes. As the summer oxygen concentration of the hypolimnion gradually decreases over time, the cisco, in order to meet its oxygen needs, is forced upward into strata with progressively higher temperatures. Eventually the combination of low oxygen in deep water and high temperatures toward the surface eliminates the habitat suitable for the cisco and the population is extinguished. In 1952 Indiana had 41 lakes with known cisco populations (Frey, 1955a). It is certain that a number of these populations have been completely extirpated since then, and it is not at all certain how long the others will survive.

The species of midge larvae associated with deep-water sediments have different requirements for dissolved oxygen, so that as the oxygen content of the hypolimnion gradually declines over time, the composition of the midge community likewise changes progressively in favor of species capable of tolerating lower oxygen concentrations. This led early in limnology to the establishment of a series of lake types based on the dominant species of offshore midges and presumably representing stages in a successional series. Fortunately the head capsules of the midge larvae, which are well preserved in lake sediments, suffice to identify the organisms to the generic and sometimes to the species levels. In general, the pattern of succession in an individual lake corresponds to the model, with species requiring high levels of oxygen occurring early in the history of the lake; these subsequently are replaced by species more tolerant of reduced oxygen; they in turn are replaced by species still more tolerant, and so on until the only species left is a mosquito-like larva *Chaoborus*, which can endure

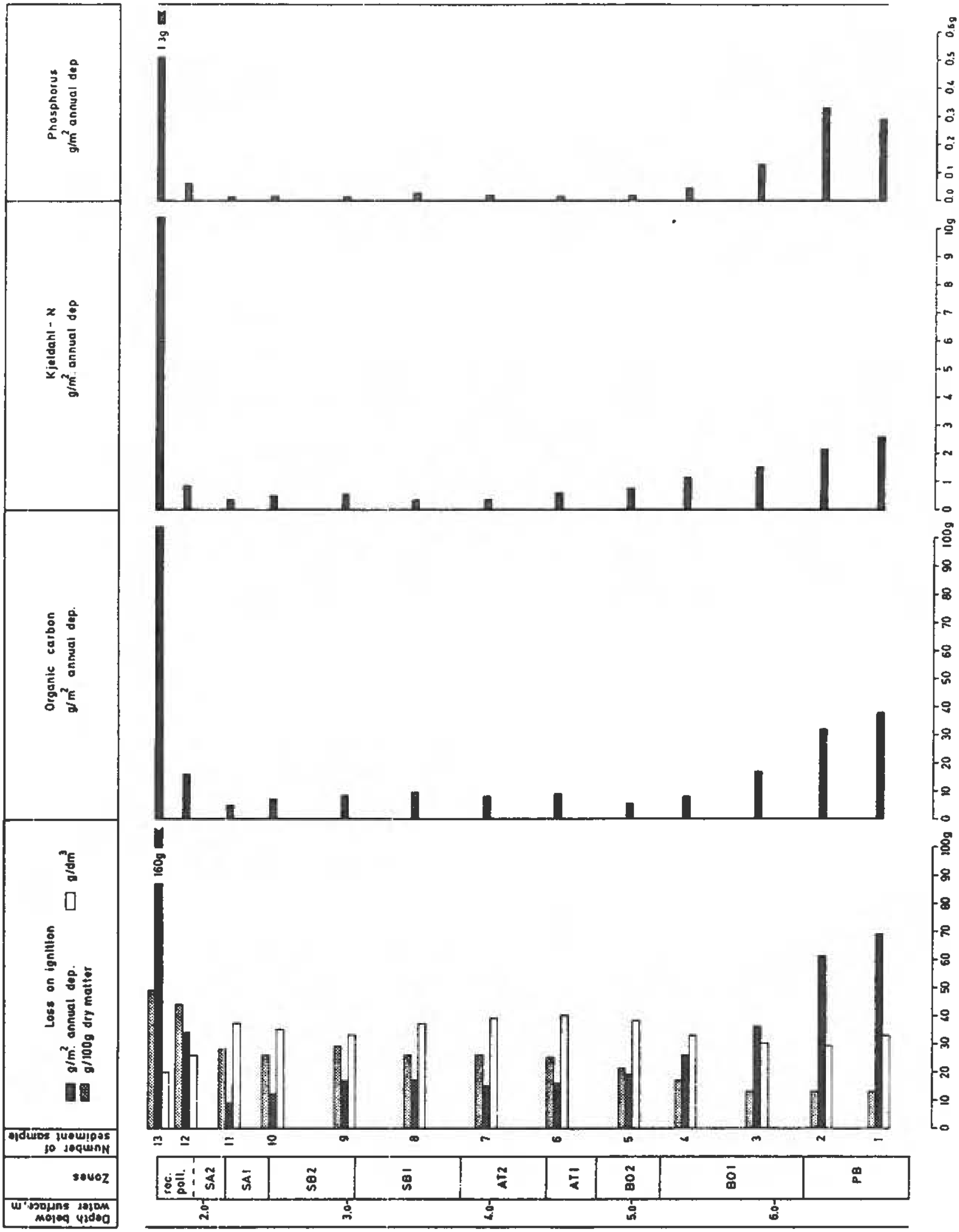

Phosphorus
g/m² annual dep
Kjeldahl - N
g/m² annual dep
Organic carbon
g/m² annual dep.
Loss on ignition
g/m² annual dep.
g/100g dry matter
g/dm³
Number of sediment sample
Zones
Depth below water surface, m
1.3g
160g
rec. poll.
SA2
SA1
SB2
SB1
AT2
AT1
BO2
BO1
PB
2.0
3.0
4.0
5.0
6.0

FIGURE 2

anaerobiosis for a while, but eventually even it is eliminated if conditions continue to deteriorate.

The most incisive study to date is that of Hofmann (1971) on Schöhsee in northern Germany. A midge community associated with moderate oligotrophy dominated the offshore community until early sub-Boreal time about 1500 B.C. This was followed by a transitional community lasting perhaps 2,500 years, and this in turn by a eutrophic community for the last 1,000 years. The whole story is much more complex than indicated by this too-brief summary in that throughout the 10,000 years of lake history there were migrations of originally shallow-water species into deep water, extinction of deepwater species, and successional dominance of one species or another as conditions gradually changed. Actual quantitative studies of the benthos in 1964-67 compared with similar studies in 1924 show that the populations are still changing (Figure 3). In this interval the population of chironomids, especially *Chironomus,* has declined drastically, being replaced by an increasing population of oligochaetes. *Chaoborus* remained about the same. This situation is reminiscent of western Lake Erie, where oligochaetes took over after the big killoff of mayflies in 1953.

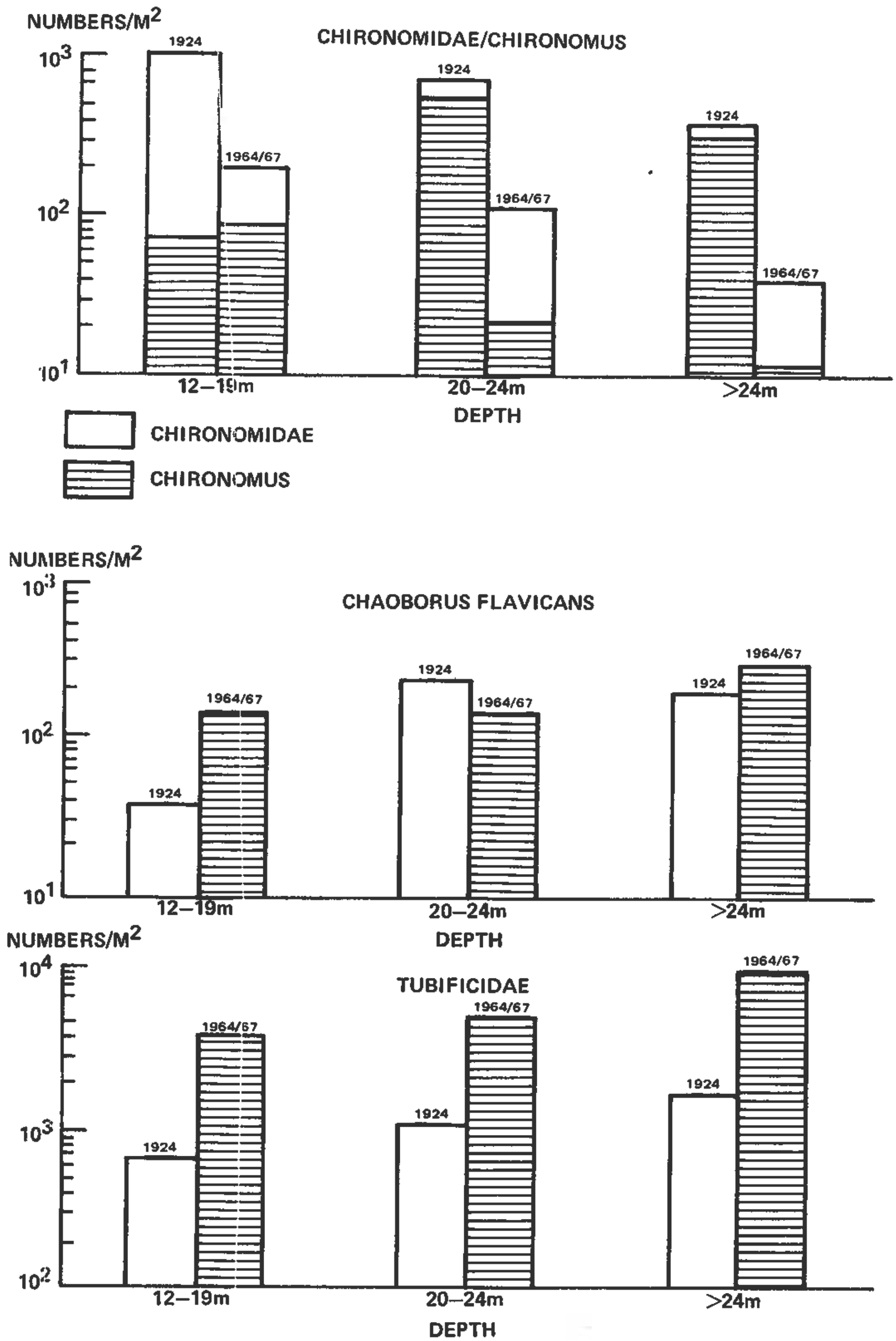
Settlers first moved into the Bay of Quinte region of Lake Ontario about 1784. Government reports describe the devastation of thousands of acres by lumbering and the erosion problems resulting. The initial impact of this land disturbance on the Bay was to change the deepwater sediment from silt dominance to clay dominance and to bring about a marked decrease in organic content through dilution by clay (Warwick, 1975). Subsequently, the organic content increased gradually, although it is still less than pre-impact level, but now there is a pronounced decline in oxygen content of the deep water in summer. The initial response of the midge community was somewhat surprising; it became more oligotrophic than it had been before but then it proceeded through several successional phases to a quite strongly eutrophic stage at present (Figure 4). Unlike previous investigators, Warwick believes that the earliest stages in midge succession are controlled by food supply more than by the minimum annual concentration of oxygen in the hypolimnion. The latter is important chiefly in the later stages of succession. Besides the shift in lithology from silt to clay, the sediments deriving from the impact period are marked by the appearance of the pollen of *Ambrosia* (ragweed), the abundance of which in the sediments roughly parallels but lags somewhat behind the curve showing increase in population of the region. *Ambrosia* provides an excellent time-stratigraphic marker in eastern North America for forest clearance and the initiation of agriculture.

Man's effect on our water resources is nothing recent. Figure 5 is a pollen diagram of Längsee in southern Austria (Frey, 1955b), a lake that presently has a layer of water at the bottom that does not participate in the circulation of the rest of the lake in spring and autumn—a condition known as partial circulation or meromixis. At a particular level in the sediments, which is obvious in the diagram, there are sudden changes in the non-tree pollens, including the appearance of various agricultural weeds and occasional grains of such cultivated plants as cereals and walnut, as well as a disruption in the development of the forest vegetation. At this same level discrete bands of clay occur, separated by a black reduced sediment completely unlike the stable sediment deposited prior to this but identical to what occurs above. Quite obviously, this is when agriculture began in the region about 2,300 years ago, and just as obviously the clearance of the land for agriculture resulted in the inwash of large quantities of clay into the lake, triggering the condition of partial circulation, now maintained by biological means. Hence, the sudden import of large amounts of clay into a lake can have different consequences for different systems.

Lago de Monterosi, a small volcanic lake in central Italy about 40 km from Rome, had an initial small burst of productivity when formed about 25,000 years ago, then a long phase of low productivity up to Roman time, when the construction of a road, the Via Cassia, in 171 B.C. completely changed the input of nutrients and other substances from its small watershed (Hutchinson, et al. 1970). The lake responded by dramatic increases in productivity and sedimentation rates which did not peak until almost 1,000 years after the disturbance (Figure 6). Since then, productivity, as inferred from the accumulation rates of such substances as organic matter, nitrogen, et cetera, has subsided to a level not much greater than that existing before the disturbance. The lag in response and the long duration of the response are probably related to the fact that Monterosi is a closed basin with no permanent streams draining its very small watershed and with output only via seepage.

Grosser Plöner See is a lake in northern Germany famous for the many studies in limnology conducted there by August Thienemann and his associates. In 1256 A.D. a dam constructed at the outlet raised the water level about 2 meters, overflooding much flatland in the process and greatly increasing the extent of the littoral zone. The response of the lake was spectacular (Ohle, 1972). The sedimentation rate, which had increased slowly from about 0.1

SCHÖHSEE BENTHOS 1924 AND 1964/67



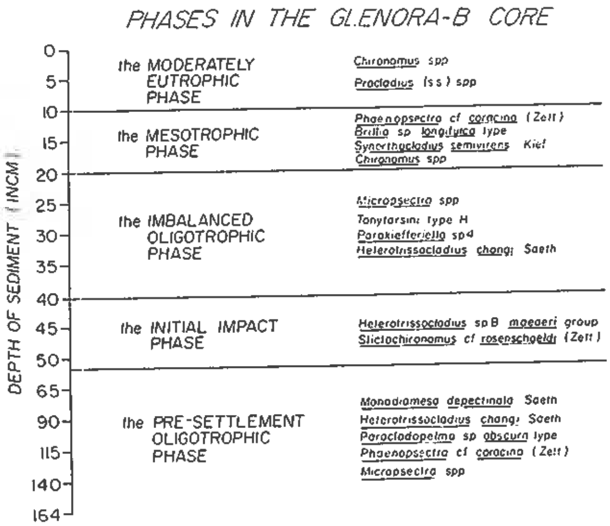


FIGURE 4

mm per year at the beginning of postglacial time to only about 0.5 mm per year 9,000 years later, suddenly jumped 20-fold to more than 10 mm per year. This has resulted in half the 15 meters of sediment in the lake deriving from only the last 700 years of the lake's existence. The big increases at this time in the accumulation rates of such substances as zinc, copper, cobalt, and aluminum reflect the increased input of mineral substances to deep water from the overflooded land and probably from the watershed' also. Correspondingly big increases in the accumulation rates of organic matter, chlorophyll derivatives, and diatom silica reflect the big increase in production within the system resulting from this changed regime (Figure 7).

The lake level had been raised to power a mill dam, as was common in northern Germany at this time, and also to facilitate the production of eels, but the concomitant flooding of valuable agricultural lands resulted in a long-continuing strife be-

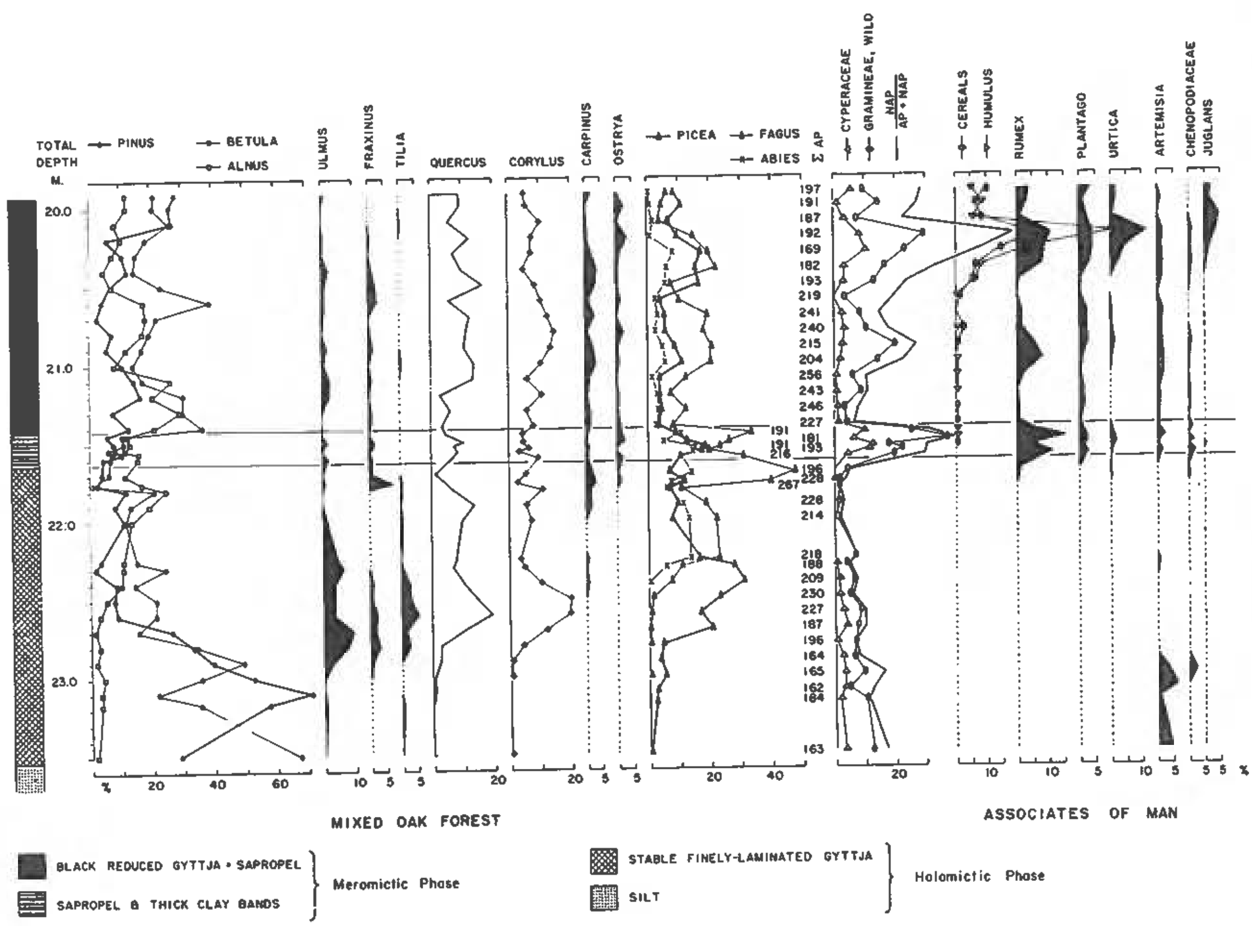


FIGURE 5

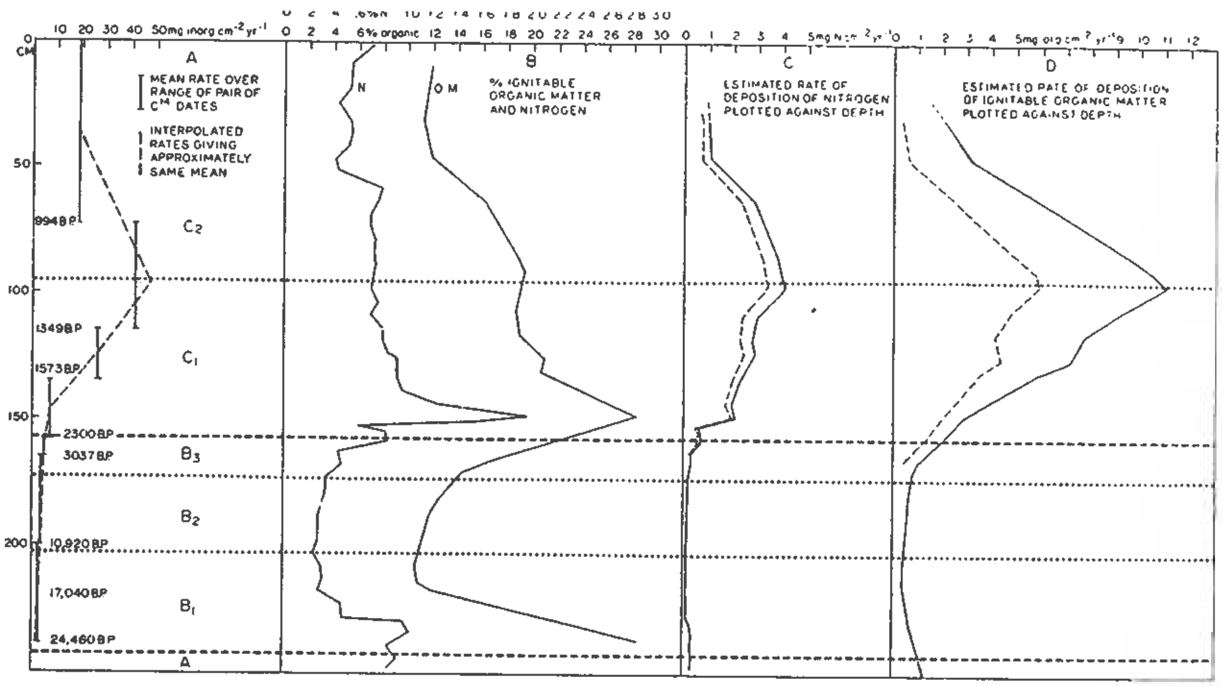


FIGURE 6

tween the mill operators and fishermen on the one hand and the manor owners and farmers on the other. Finally, in 1882 the lake level was lowered by 1.14 m. Up to this time the accumulation rates of most mineral substances had been declining irregularly, and likewise the indicators of biological activity. The sudden lowering in lake level resulted in the erosion and deposition offshore of sediments that had accumulated in shallow water, yielding a discrete horizon of coarse-grained sediments and associated sharp peaks of various mineral constituents. Accumulation rates of chlorophyll derivatives and diatom silica declined at this time, perhaps through light limitation of production by increased inorganic turbidity. The large increase in chlorophyll derivatives in very recent time, reflecting high productivity, is attributed to the heavy use of agricultural fertilizers and phosphate detergents and to the draining of the surrounding wetlands. Such an increase of organic matter and other indicators of production toward the surface is commonplace among lakes being stressed by man, frequently resulting in a completely different type of sediment than anything deposited earlier.

Grosser Plöner See is but one of a number of instances where the productivity of a lake has been markedly increased by raising its water level. The present high productivity of Grosser Plöner See is shared by many lakes of the region, all accomplished within the past few decades in direct response to man's increasing impact on the systems. Ohle (1973) has used the term "rasante Eutrophierung" (racing eutrophication) for this rapid response of lakes to cultural influences, in contrast to the generally slow, balanced development occurring naturally.

The most abundant animal remains in lake sediments are the exoskeletal fragments of the Cladocera, particularly the family Chydoridae (Frey, 1964). They are abundant enough for the construction of close-interval stratigraphies similar to those of pollen and diatoms and for the calculation of various diversity indices and distribution functions. Since the deepwater sediments represent an integration over time and habitat, the population of remains recovered from the sediments is partly artificial, in that all the species represented probably did not co-occur at the same time and place. Yet the diversity indices of the chydorids do show certain demonstrable relationships to such variables as productivity and transparency and, as shown in Figure 8, the relative abundance of the various species in an unstressed situation conforms almost precisely to the MacArthur broken stick model for contiguous but non-overlapping niches (Goulden, 1969a). Hence, the species distribution predicted by this model can be used to assess the extent of imbalance in the system.

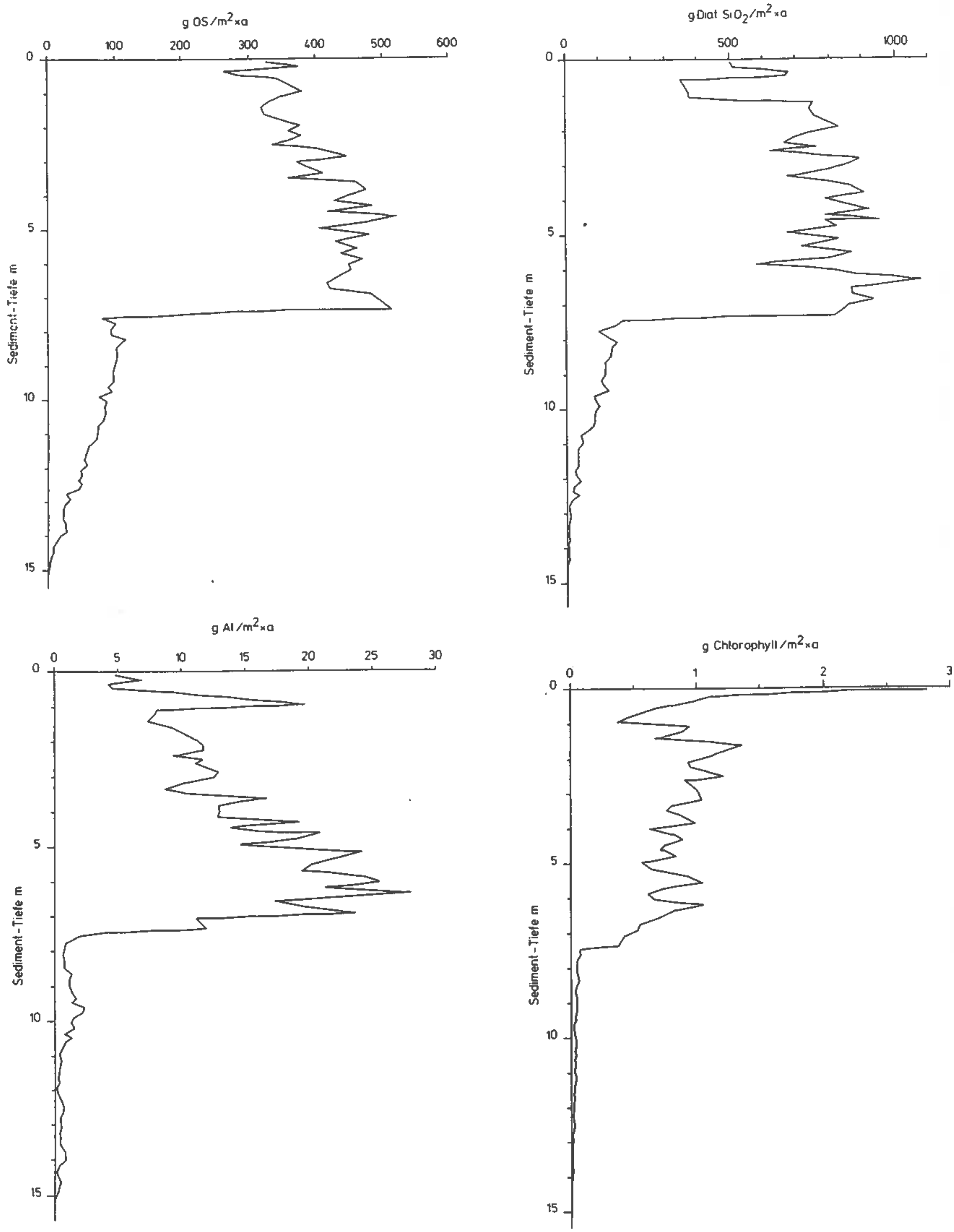

g OS/m²×a
0
100
200
300
400
500
600
Sediment-Tiefe m
0
5
10
15
g Diat SiO₂/m²×a
0
500
1000
Sediment-Tiefe m
0
5
10
15
g Al/m²×a
0
5
10
15
20
25
30
Sediment-Tiefe m
0
5
10
15
g Chlorophyll/m²×a
0
1
2
3
Sediment-Tiefe m
0
5
10
15

FIGURE 7

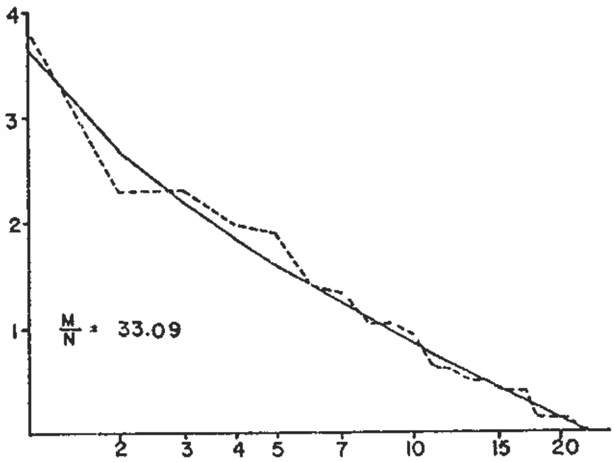


FIGURE 8

In a series of 21 lakes in Denmark for which measurements of annual phytoplankton photosynthesis by radiocarbon uptake are available (Whiteside, 1969), there is a direct relationship between species diversity and transparency and an indirect relationship between species diversity and productivity. There is also an inverse relationship between transparency and productivity. The interpretation of these relationships is that as lakes become more productive, they become less transparent from the development of larger phytoplankton populations, and with higher productivity the chydorid community is thrown out of balance, quite possibly from a reduction of habitat diversity through the curtailment of species diversity and areal extent of the aquatic plants which form the major habitat of the chydorids. And since the chydorids are but one component of a complex community, one can assume that the community as a whole has been stressed by an increase in productivity.

In another study in Denmark, Whiteside (1970) attempted to establish the predictive value of chydorid communities for lake type, and then attempted to use these results in interpreting changes in lake type in postglacial time in response to climate and vegetational patterns of the watersheds. A hard water, eutrophic lake (Esrom Sø) was sufficiently buffered internally that it went placidly about its business during postglacial time almost regardless of external stresses that would be expected to have repercussions on the system, whereas a soft water, oligotrophic lake (Grane Langsø) reacted nervously to even small external stresses. Thus, the response to a given stress can be expected to vary greatly from lake to lake depending on its particular suite of ecological conditions and balances.

The MacArthur predictive model has been used to assess community stresses resulting from the rapid climatic change of the last interstadial (Goulden, 1969a), from episodes of Mayan agriculture in Central America (Goulden, 1966), and from volcanic ash falls in a lake in Japan (Tsukada, 1967). The last study (Figure 9) is interesting in showing that a single instantaneous but massive perturbation, as from an ashfall, can have marked and long-lasting effects on the community structure of a lake.

There are quite a few other studies on the responses of lakes to stresses that might be cited, but I should like to give just one more. The paleolimnology of North Pond in northwestern Massachusetts is being studied intensively by Tom Crisman, a graduate student at Indiana University. Many major changes, almost as precipitous as those in Grosser Plöner See, occurred in the lake shortly after the pine forest represented by pollen zone B was replaced by deciduous hardwoods. Productivity in the lake, as evidenced by the quantity of chlorophyll derivatives in the sediments, increased dramatically at that time, along with nitrogen and phosphorus. A species of planktonic Cladocera, *Bosmina coregoni*, which is usually considered characteristic of more oligotrophic situations, was replaced almost instantaneously by *Bosmina longirostris*, characteristic of more eutrophic situations (Figure 10). Since there is no clear evidence for any major fluctuation in water level and since it is unlikely the Amerindians could have modified the watershed to any appreciable extent, the only correlate and possible cause is the shift in forest composition. But this is difficult to reconcile with the data, because watershed studies to date have demonstrated that deciduous forests are more parsimonious than coniferous forests in releasing nutrients from the system.

Let me attempt to summarize some of the major points developed. Lakes change biologically during their existence from changing inputs of nutrients and energy and from changing internal control mechanisms, associated in part with stratification and depletion of oxygen content in deep water. The biological changes in many instances have been gradual, although in others they have been sudden, associated with natural catastrophes, major changes in water level, or even changes in the dominant vegetation type in the watershed.

Lakes vary in their sensitivity to external stress and in their rapidity and magnitude of response. Man's chief impact is to stress the systems so severely that they are thrown out of balance and the

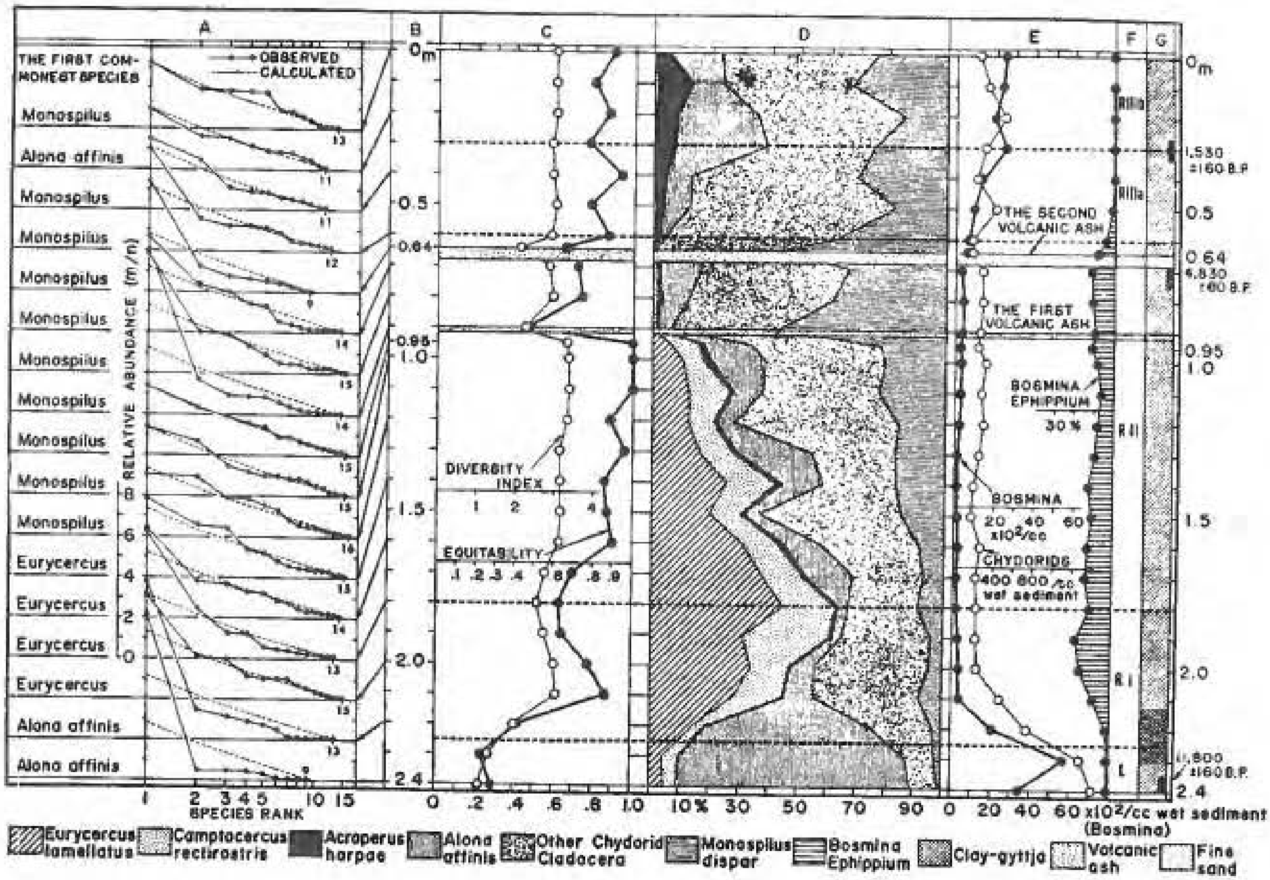


FIGURE 9

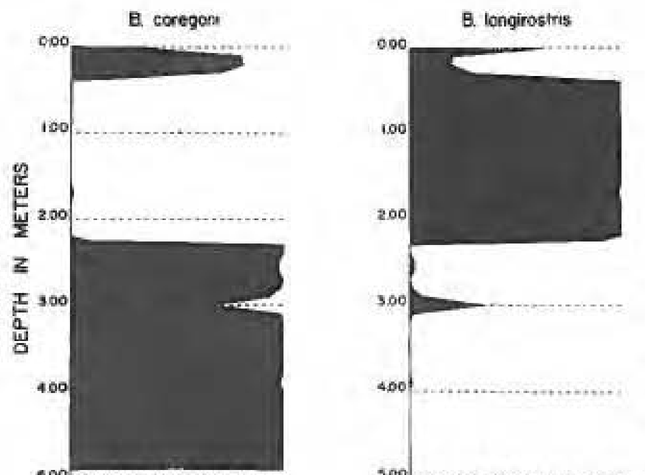


FIGURE 10

rate of change is accelerated—what Ohle calls "rasante Eutrophierung." Both for natural and man-induced stresses, the response of the total system may be fast or slow, and likewise the rate of recovery. The lag may be considerably greater than predicted from the water replacement time, amounting to hundreds of years even in small lakes if our examples from the past have been correctly interpreted. Hopefully, the response time, particularly of recovery, will be fairly short, but faced with the unpredictability of the response time, we should be much more solicitous about the stresses placed on our lakes, as even with massive engineering input they may not recover as rapidly as hoped.

Eutrophication occurs naturally, but so does the contrary process of oligotrophication. That is, a lake can become less productive with time, if its nutrient budget is decreased. Paleolimnology has not yet been able to resolve what the major controls of productivity have been in the past for any particular lake, except by inference from our knowledge of present controls. But since phosphorus, more than any other single substance, is the dominant control of productivity in temperate lakes, it is essential to keep phosphorus inputs at a minimum if we are to have any hope at all of maintaining the integrity of our lakes.

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DISCUSSION

Comment: Your definition of the integrity of water seems to be the capability of maintaining and supporting a composition of organisms that can exist in its natural state. In your discussion you described varying natural states and change of process. How does that translate to a useful definition today?

Dr. Frey: We had an example a couple of weeks ago when two young Ph.D.'s who were modeling ecosystems gave seminars at Indiana University. They had linear models which didn't allow for any change over time. However, in any particular lake there will be changes over time, induced by changes in climate and vegetation, soil development, and so forth. The response of the aquatic community to these changes will probably be adaptive adjustments in species composition and in the relative abundance of species, controlled in part by the mobility of the species. I think a definition of integrity has to include the concept of a balanced, integrated, adaptive community.

Comment: Did you go into these?

Dr. Frey: No, they are objectives.

Comment: Have you made any comparisons with other organisms over an historical period? Would you be able to use changes in the plankton population to detect changes in the water, as you pointed out is possible with fish populations? Would the changes be subtle or quite apparent?

Dr. Frey: I didn't go into any of the long term studies, because even the best of these are less than 100 years old. I know, for example, that there are records for the Chicago water supply which document the kinds and quantities of plankton in southern Lake Michigan over many decades. Probably the longest and most nearly continuous record of all is that for Lake Zürich in Switzerland. Here the deepwater sediments have been accumulating as discrete annual layers since the late 1800's. As the lake became more eutrophic under man's influence, various species of algae invaded the lake and developed to bloom proportions. These are documented by studies of the plankton. Significantly, the blooms of the various species, particularly the diatoms, are also recorded in the appropriate annual layers, so that Lake Zürich constitutes to some extent a calibration system for the interpretation of real events and changes in a lake from what is recoverable from the sediments.

Most of these long term data series have been reported elsewhere at various times. I didn't attempt to summarize them, but instead concentrated on the kinds of interpretations that can be made from the sedimentary record.

Comment: I'd like to ask you a philosophical question stemming from your definition of integrity. In your opinion, are efforts to reverse a naturally occurring trend toward eutrophication counter to the integrity of that lake?

Dr. Frey: I had to leave out a number of pages of my prepared text because of time limitations (but these are included in the published paper). For the chydorid cladocerans, which are well represented in lake sediments, the species diversity of the community declines as the productivity of the lake increases, indicating that the system is being stressed. This should not be interpreted to mean that all productive lakes are out of balance because the rate of change is probably the important consideration. Where the increased productivity is the result of man or of some essentially instantaneous event such as a volcanic ash fall, the rate of change in nutrient budgets or other environmental conditions is so great that the community cannot keep pace with orderly and adaptive adjustments. But where the forcing variables change slowly over time the aquatic biota is able to maintain an internal balance. Hence, I am in favor of either reversing the trend toward increasing productivity in our natural waters, except where this is specifically desired, or at least sufficiently reducing the rate at which eutrophication is occurring so that the system is not stressed unduly.